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A survey of decision-making approaches for climate change adaptation: are robust methods the way forward?

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Abstract

Applying standard decision-making processes such as cost-benefit analysis in an area of high uncertainty such as climate change adaptation is challenging. While the costs of adaptation might be observable and immediate, the benefits are often uncertain. The limitations of traditional decision-making processes in the context of adaptation decisions are recognised, and so-called robust approaches are increasingly explored in the literature. Robust approaches select projects that meet their purpose across a variety of futures by integrating a wide range of climate scenarios, and are thus particularly suited for deep uncertainty. We review real option analysis, portfolio analysis, robust-decision making and no/low regret options as well as reduced decision–making time horizons, describing the underlying concepts and highlighting a number of applications. We discuss the limitations of robust decision-making processes to identify which ones may prove most promising as adaptation planning becomes increasingly critical; namely those that provide a compromise between a meaningful analysis and simple implementation. We introduce a simple framework identifying which method is suited for which application. We conclude that the 'robust decision making' method offers the most potential in adaptation appraisal as it can be applied with various degrees of complexity and to a wide range of options.

Keywords: climate change; adaptation; economic decision-making; robust decision-making

1. Introduction

Climate change adaptation research has progressed significantly in the last decade, illuminating many different aspects in the field, including identifying potential adaptation options (Iglesias et al., 2012), exploring impacts under different scenarios (Stern, 2007) and identifying relevant governance challenges in policy decisions (Huntjens et al., 2012, Pahl-Wostl, 2009). But relatively few adaptation actions have actually been implemented (Wise et al., 2014). At the same time, climate change projections highlight the likelihood that humankind will have to prepare for severe changes: the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) indicates warming trajectories of global temperature will likely exceed two degrees by 2100 and a World Bank report (Worldbank, 2012) projects that the planet is on track for a four degree Celsius warmer world by 2100. These reports go beyond the conceptualisation of climate change adaptation, making an emphatic call for adaptation actions in the present. Adaptation in many sectors will be reactive as the time frame for many decisions is too short to take into consideration the long-term climate signal. Adjusting growing seasons in agriculture according to changes in climatic conditions is a classic example. A farmer can implement such changes on a yearly or seasonal basis observing the prevailing weather. But implementing such incremental adaptations may not be sufficient in the long term, when anticipatory and planned adaptation is required; for example large infrastructure projects with long life times such as urban drainage structures, dams or sea walls. In some cases, society will want to avoid threshold events, such as the extinction of certain species. Moreover, extreme events may become more frequent and intense with climate change (IPCC, 2012), which may also necessitate intervention now. Where anticipatory adaptation leads to a situation in which the system is over- or under-adapted to the future climate outcome, additional costs are incurred either through large residual climate change impacts, the waste of investment if changes are not as severe as projected, or through the failure to seize new opportunities arising from climate change. Fankhauser (2010) reviewed different studies of adaptation costs whose estimates range from around $25 billion a year to well over $100 billion for the next 20 years based on 'median' climate change. Considering that the impacts of climate change might only become more severe in the more distant future, these costs may be an underestimation, but also show the inherent uncertainty of the costs of adaptation. In the context of a global economic crisis that is only slowly receding, *a fortiori* the allocation of significant resources to adaptation needs to be carefully scrutinised to invest wisely in appropriate options. Economists strive to give investment recommendations that minimise costs and maximise benefits. In other words, to allocate resources optimally by finding the strategy that is better than any other alternative for a given situation. Decision-makers largely still use traditional economic analysis techniques for appraising adaptation investments, predominantly cost benefit analysis (CBA), which struggles to account for uncertainty. Methods that extend these tools are increasingly being discussed but applications remain relatively scarce. In this paper, we progress the existing literature on these techniques by providing a decision-making framework to guide decision-makers to the most appropriate appraisal method for their situation. We also indicate which robust methods may prove most promising as adaptation planning becomes increasingly critical.

We first summarise traditional decision-making approaches to appraise investment, describing briefly cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis, followed by the difficulties of applying these methods in the context of climate uncertainty. Section 3 then presents the conceptual basis of decision-making approaches that deal better with uncertainty, so-called robust methods. The overview is not exhaustive: it describes the methods and tools that are currently most discussed in the adaptation literature and in other taxonomies of decision-support approaches (Hallegatte et al., 2012, Herman et al., 2014, Jones et al., 2014, Kunreuther et al., 2014). We focus in particular on the underlying assumptions of these methods and on the conditions under which the methods work well, and illustrate each method with a number of applications from the literature. Subsequently, we provide a simple framework summarising which adaptation problem is best appraised by which decision-making process. In section 4, we extend the discussion on robust methods by describing the limitations of robust decision-making methods, reflecting on why they have so far not been more widely applied in real projects. Finally, we outline the potential future direction of research for robust methods, identifying which may prove most promising for policy making; namely those that find a compromise between a meaningful analysis and simple implementation.

2. Traditional decision-making approaches

Cost-benefit analysis, cost-effectiveness-analysis and multi-criteria analysis are widely used decision-making approaches in policy analysis when appraising projects.

Cost-benefit analysis (CBA) attempts to maximise the benefits for society based on potential Pareto efficiency[i]. It assesses whether it is worthwhile to implement a project by comparing *all* its monetised costs and benefits expressed over a defined time span to obtain its net present value (NPV) as in equation 1:

$$NPV(i,N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \qquad (1)$$

where N is the total number of periods, i the discount rate, t is time and R_t is the net benefits (benefits minus cost) at time t. For CBA in adaptation, climate change impacts and their value must first be estimated. For this, climate projections from coupled ocean/atmosphere general circulation models (OA/GCMs) under a range of greenhouse gas emission scenarios are downscaled. This output is then fed into impact models to determine for example changes in rainfall of or crop yields. Subsequently, the impact following the adaptation option must then also be valued, and the difference between pre- and post-adaptation impacts provides the net benefits of adaptation R_t. Additionally, the costs of adaptation must be estimated over this time period. Figure 1 illustrates how adaptation benefits are obtained.

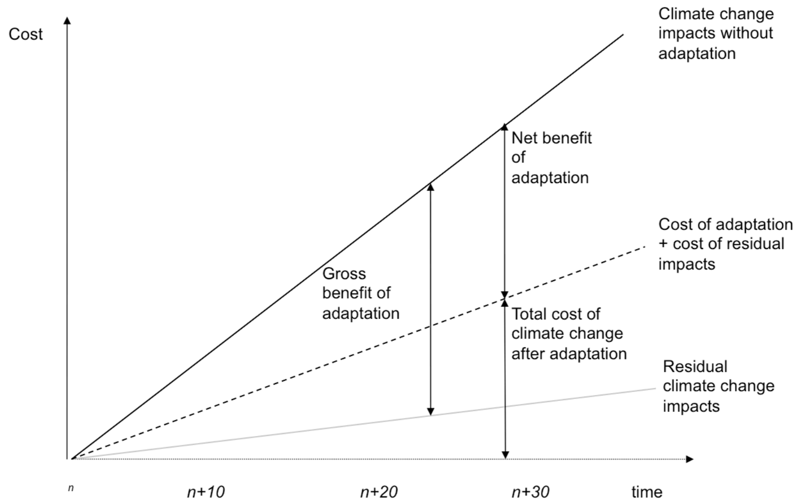

Figure 1: Costs and benefits of adaptation

The stream of benefits and costs over time are discounted to present values, and a net present value (NPV) is calculated by subtracting the net costs (cost of adaptation measure) from the net benefits (pre-adaptation minus post-adaptation impacts, thus avoided damages). A positive NPV indicates the project should generally proceed (Boardman et al., 2014). Alternatively, if the ratio of benefits to costs ("benefit-cost ratio'') is larger than one, the investment is economically desirable. Providing reliable data on costs and benefits are available, CBA can be carried out with limited technical resources and the results are accessible to a non-technical audience (for applications, see for example (Escobar, 2011) and (Willenbockel, 2011).

Cost-effectiveness analysis (CEA) represents an alternative to cost-benefit analysis when it is difficult or controversial to monetise benefits, such as the value of lives saved or landscape values. CEA compares mutually exclusive alternatives in terms of the ratios of their costs and a single quantified, non-monetised effectiveness measure with the aim to choose the least cost option. CEA is relatively straightforward in terms of optimisation: when effectiveness across all options is assumed to be identical it amounts to a simple cost minimisation problem such as achieving an acceptable level of flood protection. When the budget is fixed, an effectiveness maximisation problem is solved. For applications to adaptation, see for example (Boyd et al., 2006) and (Luz et al., 2011).

CEA works best if the benefits of the adaptation options are identical given one metric. This might apply with regard to clearly defined technical solutions. But if neither costs nor benefits are identical, scale effects need to be considered: policies with low impact at a relatively low cost per unit will be ranked higher than policies that have high impacts at a somewhat higher cost (Boardman et al., 2014), (see also Kunreuther et al. (2014) for further comparison of CBA and CEA in the context of climate policy).

Multi-Criteria analysis (MCA) in its simplest application (whose complexity can be increased in various ways) usually consists of a combination of quantitative and qualitative (monetised and non-monetised) indicators that provides a ranking of alternatives based on the weight the decision-maker gives to the different indicators (see for example Garcia de Jalon et al. (2013) for an application). For example, distributional or psychological impacts for which it is difficult to assign a monetary value can be integrated according to the preferences of the decision-maker. Results from other methods such as cost-benefit analysis can be included (UNFCC, 2009). Through the weighting, the data is mapped onto an ordinal scale and both quantitative and qualitative data can be compared relatively, but not with regard to an absolute scale, prohibiting a generalisation of the results.

CBA, CEA analysis and MCA have all long been tested, further developed and successfully applied to many projects and policies, but policy makers face considerable challenges when applying these decision-making approaches in an area of uncertainty such as climate change adaptation. While the costs might be observable and immediate, the benefits of adaptation are harder to define, as these require planning and foresight about how the climate will change. Indeed, there is considerable uncertainty attached to climate change projections, as well as to the expected impacts and responses to them (Dessai and van der Sluijs, 2007). In particular, uncertainty exists with regard to downscaled climate data such as localised data on precipitation, temperature and flood probabilities, which might not be resolved for a long time, if at all (Fankhauser and Soare, 2013). Uncertainty also stems from the future emissions of GHG, how global and local climate systems will react to these changes in emissions as well as the response of other systems to climate change, including ecosystems (Wilby and Dessai, 2010). Finally, there is uncertainty regarding knock-on effects on society and the economy depending on their vulnerability and adaptive capacity (Kunreuther et al., 2012) .

These unknowns make the application of the decision-making approaches described above at least in their 'basic' formulation challenging. The uncertainty can be addressed in different ways. For example, an expected values framework attaches "subjective probabilities" (Hallegatte et al., 2012), to evaluate the expected benefits as the probability-weighted average of the benefits based on how likely different states of the world are (Gilboa, 2009). Probabilities can be based on past occurrences of events, expert knowledge, or both. Subsequently projects matching the conditions of that future are designed and fine-tuned with sensitivity analysis. Similar to this is expected utility—if the risk preferences of those affected are known (Watkiss et al., 2014). This approach is variously labelled as 'science first' (Ranger et al., 2010), 'top-down approach' (Wilby and Dessai, 2010) or 'agree-on-assumptions' (Kalra et al., 2014) in the context of adaptation. Additionally, scenarios of how the future might unfold (of equal likelihood) can be used (Boyd et al., 2006, Garcia de Jalon et al., 2013); for CBA this is a variant to include more than the central estimate as in the expected value framework. Worst- and best cases that might be of particular interest in the context of climate change can be easily turned into scenarios. Related to this is the min/max approach that aims to minimize the possible loss for a worst case (maximum loss) scenario for prudency. Put differently, we choose the alternative such that its lowest possible expected value (i.e., lowest according to any possible probability distribution) is as high as possible (maximize the minimal expected value) (Von Neumann, 1967). Reliability-weighted expected value calculates the weighted average of probabilities, giving to each probability the weight assigned by its degree of reliability (Howard, 1988). Further variations of decisions under uncertainty exist (see Hansson (2005) for an overview) which all rely on attaching subjective probabilities to different outcomes.

All of these strategies have associated difficulties. Using several climate change scenarios provides the end-user with a range of possible outcomes, but with no attached probabilities making it difficult to make an informed decision (New and Hulme, 2010b, New and Hulme, 2010a). Expected values can be used in situations of quantifiable uncertainty. But for climate change we do not have a strong methodology to assess these subjective probabilities. They cannot be fully based on the past, because climate change is a new process for which we have no historical equivalent. Models share common flaws in their assumptions and their dispersion in results cannot be used to assess the real uncertainty (Hallegatte, 2012). The term deep uncertainty (Lempert et al., 2003) or severe uncertainty is used (Ben-Haim, 2006) in these contexts. Such uncertainty is characterised as a condition where decision makers do not know or cannot agree upon a model that adequately describes cause and effect or its key parameters (Walker et al., 2012). This leads to a situation where it is not possible to say with confidence whether one future state of the world is more plausible than another. Also, challenges can arise if there is disagreement on the ethical judgment and worldviews as objectives need to be agreed upon (based on a decision criterion) (Hallegatte et al., 2010.)

The limitations of traditional decision-making approaches for investment appraisal in the context of climate change have been recognised by many decision makers and governments. Alternative decision making approaches to appraise and select adaptation options are therefore being explored, both in the academic and policy literature (Dessai and Sluijs van de, 2007, European Commission, 2013, Hallegatte and Corfee-Morlot, 2011, Hallegatte et al., 2012, Ranger et al., 2010, UNFCC, 2009). The aim is to better incorporate uncertainty while still delivering adaptation goals, by selecting projects that meet their purpose across a variety of plausible futures (Hallegatte et al., 2012); so-called robust decision-making approaches. These are designed to be less sensitive to uncertainty about the future and are thus particularly suited for deep uncertainty (Lempert and Schlesinger, 2000). Instead of optimising for one specific scenario, optimisation is obtained across scenarios: robust approaches do not assume a single climate change forecast, but integrate a wide range of climate scenarios through different mechanisms to capture as much of the uncertainty on future climates as possible. This is achieved in different ways: by finding the least vulnerable strategy across scenarios (Robust Decision Making), defining flexible, adjustable strategies (Real Option Analysis) or by diversifying adaptation options to reduce overall risk (Portfolio Analysis). Furthermore, no or low regret options that perform well independent of the climate driver are also discussed in the context of robust methods, although they are not decision-making approaches *per se* but options.

For risk-averse decision-makers, robust strategies are attractive as they help to reduce the range of uncertainty in an investment decision. They can thus help to reach consensus on actions as different future scenarios and thus diverging viewpoints are better integrated, while reducing the risk of over- and under-adaptation. But different adaptation problems will require different techniques depending on the characteristics of the adaptation options and the nature of the uncertainty. While much discussed in the academic literature (Dessai and Sluijs van de, 2007, Hallegatte and Corfee-Morlot, 2011, Hallegatte et al., 2012, Lempert and Schlesinger, 2000, Ranger et al., 2010, Watkiss et al., 2009, Wreford et al., 2010) and in policy documents (Frontier Economics, 2013, UNFCC, 2009) so far relatively few applications exist.

3. Robust Decision-Making Approaches

3.1. Portfolio analysis

Portfolio Analysis (PA) is akin to combining shares in a portfolio to reduce risk by diversification (Markowitz, 1952). Analogously, a basket of adaptation options is determined by maximising adaptation returns given the decision maker's risk affinity. Alternatively, given a defined return of the adaptation options, risk is minimised across all adaptation options for different climate change scenarios. A portfolio is best balanced if the co-variance of the assets is negatively related, off-setting the risk under different scenarios. In other words, a low return on one asset will be partly offset by higher returns from other assets during the same period. For example, solving for minimising risk for different target returns will provide a range of feasible portfolios specifying the weights (quantity) of the different adaptation options in each portfolio. The benefits can be expressed both in monetary and non-monetary terms, for instance as conservation values of wetland habitats (Ando and Mallory, 2012), or as the potential to regenerate forests with different tree seeds (Crowe and Parker, 2008). Figure 2 shows different feasible portfolios for different target returns on an efficient frontier. In the application of Ando and Mallory (2012), the benefit axis refers to the average expected value of conservation of land while the risk axis expresses the standard deviation of the conservation values. Thus the decision maker can make an explicit choice between average expected value of return and riskiness (standard deviation of the return); the higher risk, the higher the expected value

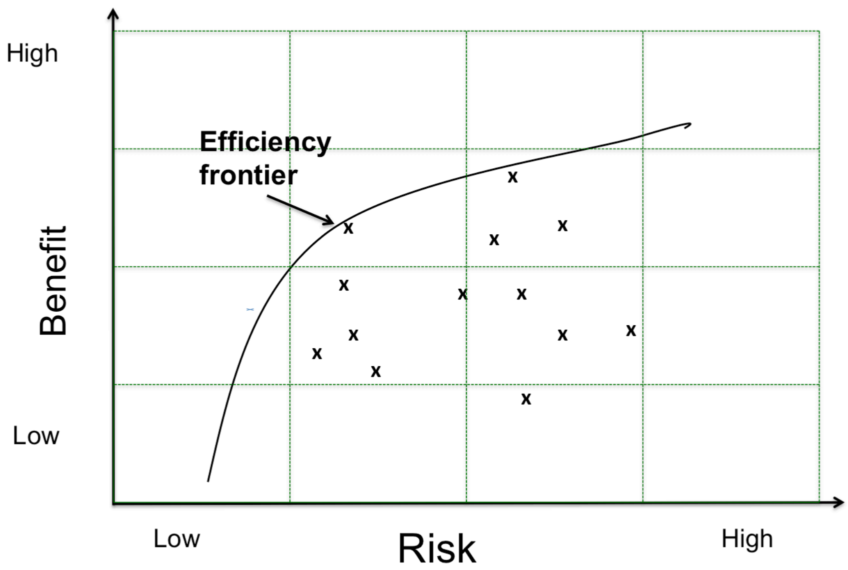

Figure 2: Efficiency frontier: a portfolio on the frontier is chosen according to risk preference.

PA thus allows a trade-off between the return and the uncertainty of the return of different combinations of adaptation options under alternative climate change projections. However PA still requires assumptions about probabilities of plausible climate change scenarios and associated impacts, and is thus still a 'predict-then act' decision-making process. The method also only works if the returns of the adaptation options are negatively correlated and their correlation can be well specified for a long term planning horizon. This might for example be a basket of locations where certain animal or plant species may be preserved.

The strict application criteria may account for the limited number of applications, which to date are focused in the area of conservation (Ando and Mallory, 2012, Crowe and Parker, 2008). But the technical requirements are not necessarily complex and returns may include both economic efficiency and physical effectiveness, so it would be worth exploring further applications. In the area of conservation management in particular, costs will often be quantifiable but benefits are likely to be much more difficult and controversial to measure. This is for example the case for ecosystem services of peatlands or forests where so far hardly any estimates exist (Moran et al., 2013) and might therefore be well suited for an application of portfolio analysis.

3.2. Real option analysis

Flexible and reversible approaches handle deep uncertainty by allowing for learning about climate change over time, and are designed in a way that they can be adjusted or reversed over time when additional information becomes available. Real Options Analysis (ROA) is one of several ways to formalize policies that adapt over time in response to new information.

Real Option Analysis (ROA) originates from financial economics (Cox et al., 2002, Dixit and Pindyck, 1994, Merton, 1973) and extends the principles of cost-benefit analysis to allow for learning based on an uncertain underlying parameter.

The uncertain parameter in the context of climate change is a specific climate variable: rainfall, temperature or sea level rise, for example. ROA analyses whether it is worth waiting for more information, i.e. it estimates the value of additional information given the uncertainty surrounding climate change, instead of possibly over- or underinvesting now. Thus, there is a trade-off between obtaining the potential pay-off in the present and waiting for further scientific information in the future (Gollier and Treich, 2003).

ROA relies on the assumption that uncertainty is dynamic rather than deep. Uncertainty is assumed to resolve to a degree with the passage of time due to increasing knowledge on climate change impacts. The idea can be illustrated in a simple decision tree as in figure 3.

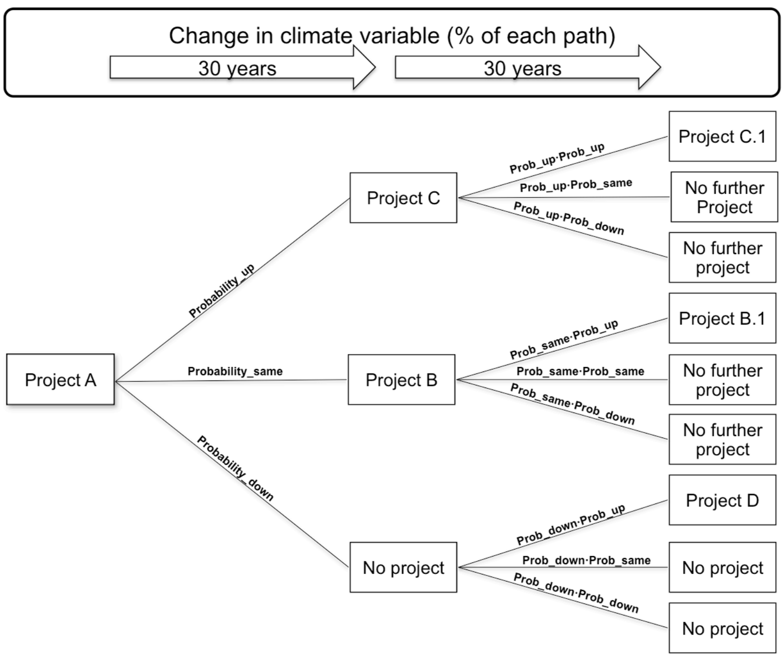

Figure 3: Real Option Decision Tree

Gersonius et al. (2013) applied this strategy to urban drainage infrastructure in West Garforth, England: the connecting lines in the decision tree in figure 3 depict the change in the climate variable rainfall intensity either upwards, downwards or remaining the same over a period of 60 years (divided into 30 year intervals). The decision nodes reflect adaptation options such as replacing sewer conduits or building and upsizing storage facilities. Given these climate paths, ROA looks at each and every possible scenario and indicates what to do in any of these contingent events, i.e. which adaptation option to implement. Thus, the strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. The aim may for example be to minimise the life-time cost or maximise the life time benefit of the specific project. Project A is the initial adaptation option and investment C should be implemented after a period of 30 years, if the climate variable turns out to follow the upward path. Subsequently a set of further projects can be implemented approaching the end of the second period. The optimal choice made during the second period is determined by the choice made in the first period. Thus, an adaptation strategy is developed that can be adjusted if needed when reassessing the strategy in 30 years and again in 60 years as different plausible scenarios will have been considered today.

ROA works particularly well for large irreversible investments with long life times and sensitivity to climate conditions, when there is a significant chance of over- or underinvesting combined with an opportunity cost to waiting, i.e. if there is a need for action in the present. It has a timeliness and a flexibility implication: first, ROA evaluates the benefits of postponing part or all of an (irreversible) investment, and second, it can assess technical options created or destroyed through the project (Wang and De Neufville, 2005).

Regarding the timing of the investment, the larger the cost of the immediate investment, the more the valuation is skewed towards postponing the investment and vice versa. Thus, if there are ancillary benefits to the adaptation strategy independent of the uncertain underlying parameter (climate risk), for example in the case of natural flood risk measures that may provide significant ecosystem services independent of the climate factor flood risk, waiting may not be worthwhile.

In terms of the technical flexibility of an investment, a flexible ‘real option’ strategy that can be adjusted over time will often be more expensive initially than a supposedly optimal single solution. But the latter might become more costly if the climate change impacts turn out differently than expected leading to premature scrapping or expensive retrofitting (Ranger et al., 2010). Unlike traditional appraisal methods, ROA does not result in a single highest ranked option as an output. It provides flexible strategies along the different climate paths that can be adjusted over time and an explicit valuation of created and destroyed capabilities (Hallegatte et al., 2012).

While relatively widely used for investment projects in the business world (Copeland and Tufano, 2004), there are few applications in climate change adaptation. These include mainly large infrastructure flood protection projects such investment in coastal protection (Linquiti and Vonortas, 2012, Scandizzo, 2011, Woodward et al., 2011). Gersonius et al. (2013) investigated the added value of real option analysis with regard to investments in urban drainage infrastructure in West Garforth, England. The strategy is adjustable and a specific implementation is chosen by observing the actual change of rainfall intensity over time. Other closely related decision-making approaches to ROA include the dynamic adaptive pathways work (Haasnoot et al., 2013), adaptive policy-making (Walker et al., 2001) as well as adaptation tipping points (Kwadijk et al., 2010) and adaptation pathways (Haasnoot et al., 2011, Haasnoot et al., 2012). They vary in terms of how they identify different climate paths, trigger points for action and design plans that can be adjusted as well as how they are presented visually.

Limited application may be related to the complexity of the appraisal process. Probabilities need to be assigned to different plausible climate change paths assuming a science-first approach. However, probabilistic data may not be available for all regions as it is for example for the UK (Murphy et al., 2009) and these depend on different emissions scenarios. Additionally, to provide quantitative results, good data is necessary: methods such as genetic algorithms or dynamic programming that usually require expert knowledge can provide solutions to the objective function. However, ROA can also be applied qualitatively by drawing up a decision tree that outlines different adaptation paths to provide conceptual guidance on the adaptation strategy. Moreover, the short term nature of decision making and budgeting both in the public and private sector work against the implementation of such long term plans with possible high up-front costs.

3.3. Robust-decision making

A policy-first (Carter et al., 2001), or also called 'vulnerability-first', 'thresholds first' (IPCC, 2012), 'context first' approach (Ranger et al., 2010) is based on the principle of first defining the objectives and constraints of the adaptation problem and its remedies. In a second step their functioning against different future projections is tested to determine the least vulnerable strategy, such as in Robust Decision Making (RDM).

The concept of robust decision making is not new (Matalas and Fiering, 1977) and has been used in different variations but it is most prominently linked to the RAND Corporation (Lempert et al., 2003). It was originally designed for decision-making in poorly-characterised uncertainty with a subsequent application to climate change adaptation (Lempert et al., 2006). The approach identifies measures that have little sensitivity to different climate change scenarios by trading off some optimality (Lempert and Collins, 2007). Figure 4 illustrates the decision-making process of RDM.

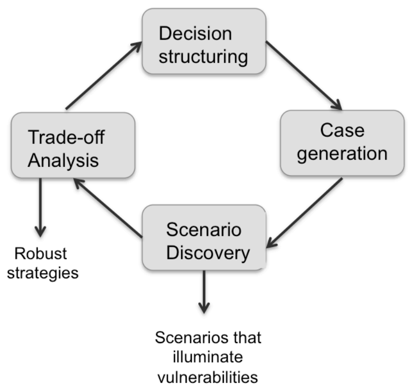

Figure 4 Conceptualisation of robust decision making (Lempert, 2013)

First, the problem at hand is structured, i.e. what is the aim of the decision-making process, and subsequently a number of potential strategies are identified. In an application of Lempert and Groves (2010) the current water management plan in the Western U.S. that aims to ensure sufficient and affordable water supply was tested. Possible management options included recycling of water, improved water efficiency and expansion of ground water. It is crucial that the uncertain parameters and their plausible ranges are identified, as these will define the vulnerability of different strategies. For the case study, beside a wide range of climate change scenarios, future socioeconomic conditions, the agency's ability to implement the plan and costs went into the analysis based on climate change projections and expert knowledge for management options. Simulation models are used to create large ensembles (thousands or millions of runs) of multiple plausible future scenarios from the parameters without assuming a likelihood of the different scenarios. The costs and benefits of different strategies are determined with the use of a value function (Lempert and Schlesinger, 2000, Lempert et al., 2006, Lempert and Groves, 2010). Subsequently, the different strategies are tested against a robustness criterion, which may be that the strategy performs well compared with alternative strategies in many different future scenarios, or a certain cost-benefit measure (Lempert and Schlesinger, 2000). For the California study, supply and demand metrics as well as per-unit costs to each of the water supplies (including efficiency) to estimate total costs to the region for consuming and disposing of water were used. In an iterative process, the candidate strategies can be adjusted and fed repeatedly through the ensembles. Accordingly, RDM does not predict uncertainty and then rank alternative strategies, but characterizes uncertainty in the context of a specific decision: the most important combinations of uncertainties to the choice among alternative options are determined in different plausible futures. As a result of the analysis, trade-off curves compare alternative strategies rather than providing any conclusive and unique ordering of options. In California, the trade-off curves also included the (political) effort needed to implement certain measures through weights. RDM thus also considers the precautionary principle by illuminating the risks and benefits of different policies (Kunreuther et al., 2014). Generally, a strategy that performs well over a range of plausible futures might be chosen over a strategy that performs optimally under expected conditions. Other approaches closely related to RDM include Decision-Scaling (Brown and Wilby, 2012) Info-Gap (Ben-Haim, 2006) and Many-Objective Robust Decision Making (MORDM) (Kasprzyk et al., 2013). They differ in terms of alternative generation, sampling of states of the world, quantification of robustness measures, and sensitivity analysis to identify important uncertainties (see Herman et al., 2015 for further comparison of the approaches.). Interestingly, Kasprzyk et al. (2013) conduct a multi-criteria portfolio analysis within a robust decision making context to provide decision support approach. They present pareto surfaces to decision makers and allow them to decide where on the surface they would like to reside. Figure 2 can be interpreted as a MCA pareto frontier where the return will consist of an array of factors.

RDM applied fully quantitatively is very data and resource intensive. For example, for the development of the water management plan in Southern California an investment of between $100,000 (where a simulation model already exists) and $500,000 (where the model needs to be developed) (Hallegatte et al., 2012) was suggested. The development of the simulation models, the metrics, acceptable risks, the benchmark for testing the strategies, as well as plausible scenarios and their upper and lower bounds need to be clearly defined. Choosing all these parameters implies that assumptions about plausible values need to be made in RDM whose range is up to the decision-maker's discretion and may thus introduce a subjective view about the future.

In the literature Groves and Sharon (2013) used RDM to develop a set of coastal risk-reduction and restoration projects in Louisiana, U.S. given a budget constraint. In an application to flood risk management in Ho Chi Minh City's Nhieu Loc-Thi Nghe canal catchment, Lempert et al. (2013) evaluated that the current infrastructure plan may not be the most robust strategy in many plausible futures emphasising the importance of adaptively using retreat measures. A further application includes determining water management strategies such as Lempert and Groves (2010) and (Mortazavi-Naeini et al., 2015). The former study tested the current water management plan in the Western U.S. that aims to ensure sufficient and affordable water supply. Besides a wide range of climate change scenarios, future socioeconomic conditions, the agency's ability to implement the plan and costs went into the analysis.

There are some studies that apply RDM in a simplified form, trading off data requirements while retaining the principle of policy first analysis. A study on evaluating natural flood risk measures in North Yorkshire, UK (Frontier Economics, 2013) made an attempt at simplifying robust decision making by reducing the number of climate change scenarios included. Matrosov et al. (2013) use RDM to select portfolios of water supply and demand strategies in the Thames water system, UK, simplifying the methodology by considering a smaller number of options but considering different uncertainties (hydrological flows as well as demand and energy prices). (Bonzanigo and Kalra, 2014) showed that the data and tools typically used in classic economic analyses such as CBA can be used while applying the principles of RDM with an application to an Electricity Generation Rehabilitation and Restructuring Project to improve Turkey's energy security. Prudhomme et al. (2010) integrated the idea of vulnerability first by testing the sensitivity of catchment responses to a plausible range of climate changes instead of focusing on time-varying outcomes of individual scenarios. This includes scanning over a range of relevant climate parameters to identify the amount of change that would cause a proposed policy to fail which can the be combined with model projections for plausibility (Brown and Wilby, 2012, Groves et al., 2013)

3.4. Robust options by design: No/Low Regret

A further way of circumventing the difficulty of characterising uncertainty is the generation of alternatives that are robust due to their characteristics irrespective of the approach to appraise them. These options may be an alternative in the short term to handle climate change uncertainty. No regret options (also labelled early benefits (Fankhauser and Soare, 2013), avoid the necessity of quantifying climate change impacts. Instead these robust options will yield social and/or economic benefits irrespective of whether climate change occurs delivering benefits now and building future resilience (Watkiss and Hunt, 2014). The options are usually specific to the adaption problem. Typical examples include fixing leakages in water pipes or water use efficiency improvements in areas that already suffer from long-run drought and increased demands independent of climate change (Hurd, 2008). With quickly visible benefits, decision makers are likely to implement no-regrets options more readily in contrast with other less robust adaptations. Indeed, no-regret options are often considered best practice and should be implemented in any case as a first step towards increased resilience. Assessing the net benefits of such adaptation options can be carried out with CBA, CEA or MCA.

While the concept of no regret options initially appears relatively uncontroversial, it is unclear what low regret options comprise (Preston et al., 2015). They may have low costs, some benefits now and in the future, or they may be options that lead to future benefits or offer benefits across most climate scenarios (Watkiss and Hunt, 2014). Different (sometimes controversial) examples include building adaptive capacity, such as measures to deal with heat stress in cities and irrigation. However, irrigation may become a maladaptation if too much water is extracted or resources might be wasted if heat stress is over-estimated when traditional predict-then-act approaches for appraisal are applied. Watkiss and Hunt (2014) argue that potential low-regret measures need to be framed in an iteratively adaptive way i.e. integrating the idea that we know best about the near future and less about the distant future. For instance, soil and water quality improvement are low regret options handling current climate variability; investing in upgradable infrastructure with respect to medium-term climate change, and on-going research on climate change with respect to the distant future.

3.5. Reduced decision-making time horizons

Another alternative to reduce uncertainty includes the generation of adaptation alternatives with reduced decision-making time horizons. The aim is to be able to adjust the action over time through several short time horizons decisions based on the assumption that this might be less costly then few large long-term decisions. Examples include lower quality and thus cheaper housing in flood prone areas (although this may also be a maladaptation in terms of the wasted resources and energy used). In forestry, shorter rotation species can be chosen to reduce time horizons as neither safety-margins nor reversibility are feasible (Hallegatte et al., 2012). Similarly, some soft options can reduce decision-making time horizons, for example the use of insurance markets to protect against flooding in the short term (UNFCC, 2009). The robustness here lies in the fact that the features of the adaptation options will likely provide benefits in the short term. Shortening the decision time horizon converts deep uncertainty to potentially quantifiable uncertainty that can then be assessed with appraisal methods that aim for optimality. The strategy can then be revised and adjusted in the future when more information might be available about climate change impacts. However, similarly to low regret measures the question of which measures actually fulfil the reduced decision time horizon characteristics arises, and related to this the extent to which traditional appraisal methods can be employed.

3.6. Which method for which situation?

It is clear that that different approaches will work well in different circumstances, depending on the characteristics of the adaptation options being considered, the data available, and the time and skills available to the decision maker.

To help identify the appropriate method for a particular adaptation project, Figure 5 presents a simple framework encapsulating the mechanisms of robust decision-making approaches, helping to identify which method will perform well contingent on the characteristics of the available options. This framework presupposes that an area of vulnerability and the adaptation question has been clearly framed, whether this relates to investment in adaptive capacity or infrastructure measures. Also, the available data and their format need to be known (Ranger et al., 2010). It should be clear that any chosen adaptation option should not be in conflict with (emissions) mitigation measures (Smith and Olesen, 2010). The framework also reflects that robust decision-making approaches may not always be feasible and traditional appraisal methods may still work best in some situations due to data limitations and the nature of the adaptation options.

To determine the most appropriate method the adaptation options are characterised according to their scale, level of uncertainty and data availability. The questions must be answered with the available adaptation options in mind. Some adaptation options may be suited to two or even three appraisal methods.

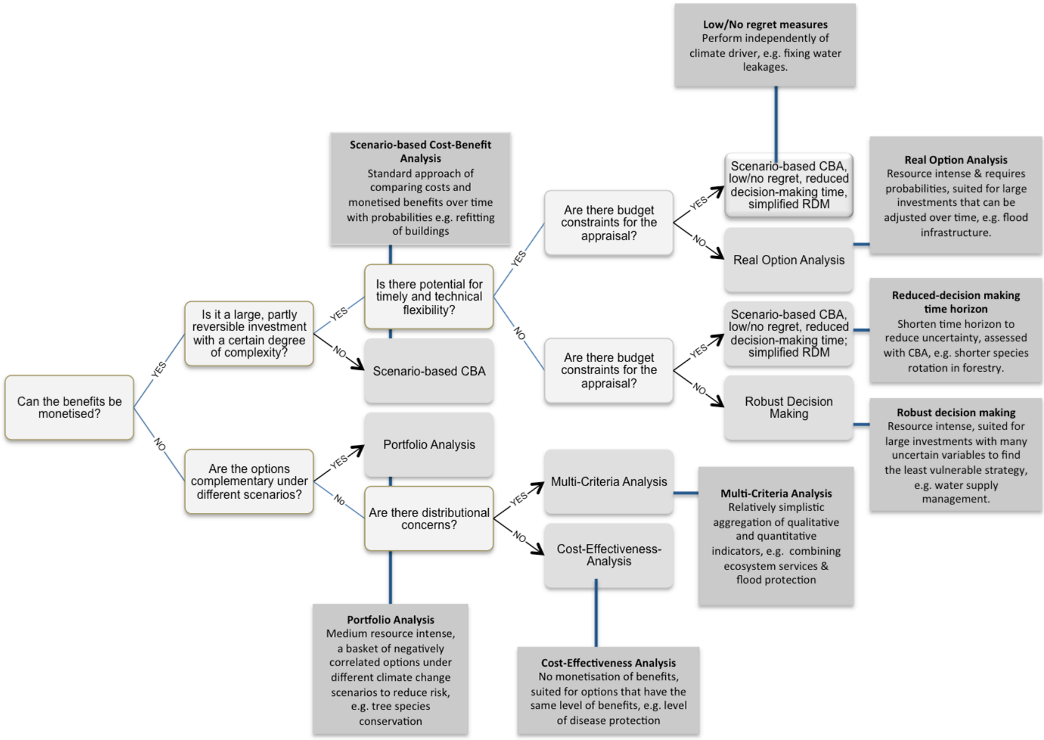

Figure 5 Finding a suitable appraisal method for adaptation options (Adapted from DEFRA (2013))

4. Discussion

It is clear that different appraisal methods work well for different adaptation problems. The framework highlights that RDM and ROA, which are relatively resource- demanding might not be feasible if there are budget constraints: either a simplified application of the methods or a traditional appraisal method may need to be used. For example, assuming benefits can be monetised (step 1) but the potential investment is relatively small (or reversible) (step 2), the expenditure for a robust appraisal may not be justified. If the investment is large and (partly) irreversible and timely and technical flexibility exists (step 3), ROA may be suited, providing there is no major constraint on budget/time for the appraisal (step 4). If this is the case, one may have to revert to one of the less resource intense appraisal approaches (step 5). At the same time, while it is important to choose an appraisal method matching the characteristics of the adaptation options, it is also crucial to recognise that different methods may resonate with different audiences, as they employ different means of communicating decision options and uncertainty. For example, MCA is useful for stakeholder inclusion and can be easily explained to a non-technical audience but the inclusion of climate uncertainties will remain simplistic. Whereas interpreting the results of RDM can be demanding but will provide a comprehensive picture of the various vulnerabilities of strategies. It should be noted that traditional decision-making approaches lead to specific actions that ought to be implemented based on decision criteria founded in rationality (e.g. highest positive NPV) whereas some of the robust decision-making approaches provide decision support instead (Lempert, 2014) Using the definition from the National Research Council (2009), this represents "the set of processes intended to create the conditions for the production and appropriate use of decision-relevant information." In particular RDM but also PA focus on the goal of providing actionable information to decision makers, who will then make their own decisions (e.g. trade-offs between options).

Second, despite delivering robust adaptation options and strategies across a range of climate change scenarios, robust methods still require assumptions about climate change scenarios. This seems contradictory at first, as robust methods are designed to handle situations of deep uncertainty (i.e. the absence of reliable data), but for a meaningful analysis it is necessary to clearly specify the range of uncertainties (to the extent this is possible).

ROA and PA are based on predict-then-act, science-first foundations. Both methods require impacts first, usually employing probabilities to describe different but nevertheless limited numbers of climate change scenarios and the adaptation strategy is optimised given the potential climate variability. Both methods then deliver robustness by integrating different climate change scenarios when appraising and simultaneously developing adaptation strategies: ROA by creating adjustable adaptation strategies for different climate change scenarios and PA by implementing a basket of adaptation options suited to different climate change scenarios. Nevertheless, the choice of the climate change scenarios considered and possibly also the probabilities for different climate change outcomes are the subjective decision of the analyst and need to be justified. Similarly, for policy first approaches such as RDM that start out with candidate strategies and not impacts it is still necessary to define the range of climate change risks the strategies are tested against. While considering these different climate change risks can help to explore the scenario space further, it nevertheless implies to an extent a valuation of how extreme the climate changes might turn out to be. Moreover, depending on the concrete adaptation problem at hand considering a very wide band of climate change scenarios can lead to a least vulnerable solution that has low benefits in the climate that actually occurs, as the benefits are considered across scenarios. This point highlights that there is a trade-off between optimality (i.e. choosing a strategy that perfectly matches a certain state of the world) and robustness, and we do not necessarily face a binary choice between an optimal or robust strategy, but rather the objective is to determine the lowest level of trade-off between optimising returns and robustness (Lempert et al., 2003). Weaver et al. (2013) point in this context to the importance of using climate models more intensively and to explore complex systems and their uncertainties. This does not necessarily imply improving projections, which will always suffer from some uncertainty (Dessai et al., 2009), but for example considering a larger set of climate models (Rajagopalan et al., 2009), comparing results from downscaling techniques (Steinschneider et al., 2012), or running a deeper sensitivity analysis to various components in the modelling chain (Dessai and Hulme, 2007), which could ameliorate the use of climate models. The IPCC suggests applying a science-first approach when uncertainties are shallow, and a policy-first approach when uncertainties are deep (Jones et al., 2014).

Third, robust methods are still relatively novel in the academic and policy agenda for adaptation. It is therefore not surprising that planners are as yet unfamiliar with the application of these methods. It takes time to become familiar with new concepts, moving away from traditional appraisal methods. But it is also true that the application of robust methods is in general more complex and time-consuming than carrying out a cost-benefit analysis. Robust methods often require a large amount of (monetised) data and the actual appraisal process might involve relatively complex mechanisms. Examples include the application of genetic algorithms in real option analysis (Gersonius et al., 2013), or solving the value function in robust decision making (Lempert and Groves, 2010). Portfolio analysis requires the specification of standard deviations of the different adaptation options. A simplification of these approaches is needed to make them more accessible to a broader audience. Indeed, real option analysis has already been simplified for its application beyond financial options to real investment projects (Cox et al., 2002) and this could potentially be further developed for adaptation. The development of different flood defence options for the Thames Estuary 2100, England (Environment Agency, 2011) used the principles of real option analysis by applying iterative adaptive management: the plan is flexible to a changing climate because interventions can be brought forward in time, alternative pathways can be included, and existing structures can be extended. While the analysis within the different components was carried out with CBA, the overall project was designed in a flexible way to allow for adjustments. (Haasnoot et al., 2013) use the principles of ROA by exploring and sequencing a set of possible adaptations based on external developments in their frameworks of 'Adaptive Policymaking' and 'Adaptation Pathways' as a guidance for decision-makers.

Similarly, there are some studies that apply robust decision making in a simplified manner as mentioned above (Bonzanigo and Kalra, 2014, Frontier Economics, 2013). Indeed the body of policy first approaches (including RDM) appears to have the greatest potential to become mainstreamed among the body of robust methods to decision-making. The principle of starting out with strategies and testing them against uncertainties can be simplified at many points in the analysis. This includes the range of climate scenarios and other uncertainties as well as the number of strategies. While there is also strong academic interest in the other robust decision-making approaches, particularly real option analysis, reflected in the range of studies in this field, it is not obvious that they can be simplified as well as policy-first approaches. Even more importantly, policy-first approaches can be applied well to most adaptation challenges if the options are well differentiated - not necessarily the case for the other approaches.

Despite its advantages however, the application of simplified RDM is also a learning process: from understanding how to structure a robustness analysis, to learning software that aids in scenario discovery, to interpreting the results of scenario discovery, to communicating the idea of trade-offs to stakeholders (Bonzanigo and Kalra, 2014).

In summary, the development of simpler and more generic toolkits for the quantitative application of robust decision-making methods is still in its relative infancy. Thus, the relative size, impacts and risks of the adaptation project need to be taken into account when choosing a decision-making method. While it is doubtlessly worthwhile to apply quantitatively robust methods for long-lived large investments, for example in infrastructure or spatial planning, decision-makers might resort to no/low regret measures or reduced decision-making time horizon options where feasible in the short term, which can be assessed with CBA as emerges from figure 5.

It should also be clear that robust methods cannot accommodate challenges that are intrinsic to any appraisal method. This includes the question of using an appropriate social discount rate when valuing the benefits accruing for future generations (Pearce and Ulph, 1998) but also the challenge of valuing environmental goods in monetary terms (Garrod and Willis, 1999). More generally all methods are based on incremental changes. Broader questions such as the socio-economic assumptions on which modelling of a distant future should be based or the policy goals of decision-makers in the future (Lempert and Groves, 2010, Wise et al., 2014) are out of reach for these methods. Certainly, climate change is often only one driver when decision-makers consider investment decisions, implying that the costs and benefits need to be studied in a wider context. For example, the demand side is crucial for water supply beyond climate change.

Finally, it should also be noted that further factors may hamper the adaptation option appraisal and ultimately the implementation of adaptation action, including behavioural barriers (Grothmann and Patt, 2005, Adger et al., 2009), the lack of institutional leadership and cooperation (Moser and Ekstrom, 2010), historical path dependency (Abel et al., 2011), or the lack of financial and human resources to implement adaptation actions (Bryan et al., 2009b, Kabubo-Mariara, 2009, Bryan et al., 2009a) amongst others.

5. Conclusion

Where planned adaptation to climate change is necessary, decision makers need to move away from striving for solutions that assume an investment today will necessarily match the actual state in the future. Uncertainties surrounding climate change projections and impacts, as well as changes in emissions in the future, mean that these assumptions will be invalid. Taking these uncertainties on board, decision-makers should consider more robust decision-making methods instead of standard cost-benefit analysis, cost effectiveness analysis or multi-criteria analysis. Robust approaches do not assume a single climate change projection, but integrate a wide range of climate scenarios through different mechanisms to capture as much as possible of the uncertainty on future climates. We have presented a range of robust methods, describing their characteristics, applications and limitations: while providing performance across a range of climate change scenarios, they may yield lower overall performance if compared with the alternative strategy under the actual climate outturn, and a well-defined scenario space is indispensable. Moreover, decision makers need to balance the resources required for employing the methods with the added value they can offer. The body of policy first approaches appears to have the greatest potential to be mainstreamed. They can be simplified at many points in the analyses and applied to a wide range of adaptation problems. Academia has an important role to play in this by further improving the accessibility and demonstrating the general applicability of these methods, and by developing more generic toolkits.

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[i] An allocation is Pareto efficient if no alternative allocation can make at least one person better off without making anyone else worse off.